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CONSIDERATIONS FOR THE USE OF COLOR IN
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**TECHNICAL REPORT
HUMAN FACTORS CONSIDERATIONS
FOR THE USE OF COLOR
IN DISPLAY SYSTEMS**



January 5, 1975

HUMAN FACTORS CONSIDERATIONS
FOR THE USE OF COLOR
IN DISPLAY SYSTEMS

Sylvester A. DeMars, P. E.
Systems Engineering Division
Directorate of Design Engineering
John F. Kennedy Space Center, NASA

FOREWORD

This study was developed through extensive document research and consultation with medical and engineering personnel experienced in the design and use of information display systems. Its intent is to identify and assess those human factors considerations which would be useful in deciding whether color should be used in the alphanumeric or graphic display of computer-generated information. The approach taken for presentation of the study results in this report is to define a display system, consider the available information relating to human factors having design impact, and then to evaluate these factors in terms of respective advantages and disadvantages associated with the use of color (as against black and white) for information displays. Because the human eye is a key design constraint in any display system, a brief discussion of the process of vision is included in this document.

A complete listing of documents researched in the study appears at the end of this report; the data sources are numbered sequentially, and those cited in the report are referenced by number.

In addition to acknowledging his indebtedness to the various domestic and foreign authors whose works contributed to this study, the writer wishes to express particular thanks to Mr. Walter E. Parsons, NASA, and Dr. D. Goodman, Project S²E, for special help in its preparation.

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SECTION I

SUMMARY

1.1 GENERAL

This report contains the results of an investigation to identify and assess those human factors considerations impacting an operator's ability to perform when information is displayed in color as contrasted to monochrome (black and white only). The findings should provide valuable guidelines for the assessment of the advantages (and disadvantages) of using a color display system.

The use of color provides an additional sensory channel (color perception) which is not available with black and white. The degree to which one can exploit the use of this channel is highly dependent on available display technology, mission information display requirements, and the acceptable operational modes.

Only the human factors aspects are considered in this study. Other factors such as display technology, alternate design approaches, requirements, and systems costs are essentially disregarded to allow an indepth, objective assessment of the value of color itself in information display systems.

1.2 CONCLUSION DRAWN FROM STUDY RESULTS

- a. For certain applications, operator performance can be improved through the use of color in terms of accuracy, decision time, and workload capability. Many sources confirm that color coding of class and group information is superior to any other commonly used forms of coding. Search and counting times are significantly reduced while greater reading accuracy is achieved. Maximum benefit from color coding of class data is realized when high-density information is displayed in a random format. A person's visual mechanism and psychological and motor responses function in such a way that if he knows the particular color of immediate concern, his entire attention will be drawn immediately to items of that color; he will be able to treat all other items as part of the background, thus restricting his attention and the area of the display over which his eyes must scan to locate a particular item or items of interest.
- b. The attention-getting qualities of color can be used effectively in coding displayed action items such as out-of-tolerance data and emergency situations. Although color is extremely effective for this application, there are other coding methods and operational modes that can produce satisfactory results when a black-and-white display is used.
- c. When a requirement exists for process control and monitoring, a color display can improve operator performance in terms of comprehension and decision time. In a process display, comprehension is enhanced

through the use of color contrast and color changes to identify functions, changes in state, and flow processes. If this task were performed with a black-and-white display either intensity or some form of geometric coding would be required. These forms of coding are considered inferior to color coding for this application.

- d. For a given symbol or group of symbols displayed in color, the information content can be increased considerably where the amount of information is a function of the number of discernible colors and the number of symbols used. However, there is a practical limit to the degree to which the information content can be increased before the coding scheme becomes too complex to use, especially with compound coding schemes. Another factor that must be considered is the additional area required for the display of colored symbols. For symbols such as alphanumerics, the area required would be greater than that required when the same information is displayed in black and white under threshold conditions. Therefore, the actual gain in information content is partially lost through the requirement for greater display area.
- e. Color blindness is not a significant factor that should influence a decision whether to use color in an information display system. Results of this study show that screening procedures used to identify operators with serious color vision defects would only eliminate or limit functions performed by approximately three to five percent of the total screened. However, the number and spectral value of colors used with an information system must be properly selected to accommodate color normals as well as mildly afflicted color-deficient people.
- f. One apparent disadvantage of displaying information in color is the larger size symbols or target area required to enable the observer to reliably perceive both detail and color. For the display of alphanumeric characters on a black-and-white CRT, a minimum theoretical visual angle of five minutes of arc is required. For the same characters displayed in color, the visual angle required would be in excess of 15 minutes of arc for reliability in color perception. However, the significance of this point is questionable since the five minutes of arc required for black and white is based on ideal threshold conditions.

Based on published human factors engineering design criteria, it is recommended that alphanumeric and geometric symbols subtend visual angles of 10 to 20 minutes of visual angle for black and white to achieve good legibility. For high reading accuracy a minimum of 15 minutes of visual angle is recommended. From this one may conclude that for a given area the number of symbols that could be displayed in color would be equal to or fewer than the number possible in black and white. The final choice of character size will depend on the display device used and the tolerable legibility and accuracy performance. The extent of this deficiency, when using color, should be verified by experimental tests.

- g. In this report only the human factors aspects of color display were considered. Color display technology is a significant factor that must be considered in the final analysis. Although many advantages were cited in this report supporting the use of color in an information display system, the degree to which these advantages could be exploited would depend in a large measure on available display devices. Possibly the most readily available device, at the present time, is the commercially available color TV cathode ray tube. The shadow mask CRT, as presently marketed, would provide a resolution of about one third that obtainable with a monochrome tube; characters and symbols displayed would be larger in color with a resultant decrease in the amount of information displayed for the same viewing area. Also, the dot pattern exhibited by the shadow mask tube may be distracting within close viewing distances. (These comments are not intended to reflect present state-of-the-art in color display devices. They are included only to identify some of the tradeoffs that must be considered when attempting to implement a color display system.)

The details supporting the conclusions appear in the subsequent sections of this report.

SECTION II

THE INFORMATION DISPLAY SYSTEM

2.1 GENERAL

The display device--for example, a cathode ray tube used in an information display system--is the principal interface between the observer (operator) and the computer or other device generating the information to be displayed. Through this interface man and machine are able to communicate with each other in such a way as to perform the operational task for which the system was designed.

To perform this task most effectively and efficiently, the visual information encoded on the face of the display device must be transmitted to the observer in such a way that the rate, quality, and form of the perceived information are optimized and made compatible with the visual capabilities of the observer, the mission requirements, and available display technology.

2.2 DISPLAY PERFORMANCE FACTORS

The rate at which information is transmitted to the observer is specified in terms of bits per second (or, in less formal terms, the number of measurements, states, characters, or symbols transmitted per unit time). The quality of the displayed information is usually measured in terms of resolution (definition), contrast ratio, brightness, color, information density, legibility (ability to read), effects of ambient lighting conditions, viewing distance and position, amount of flicker, and any other quality factors that would impact on the operator's ability to perform. The form of the displayed information is specified in terms of character font type, size of characters, line spacing, aspect ratio of the characters, and line or stroke widths. In general, form includes the format of the displayed information, i.e., the type and arrangement of characters, symbols, or graphic information appearing on the face of the display device.

2.3 DESIGN OBJECTIVES

In the design of a display system we strive to obtain an optimum match between the display device with the information it contains and the operator who has limited perceptual capabilities and human responses. Most good human factors engineering handbooks contain the necessary information and design criteria to achieve this objective; several are listed as references in this document. However, the primary concern of this study is the impact of using a multicolor display device instead of a monochrome device for the display of information. This requires an examination of those vision factors that impact on a normal person's ability to reliably perceive, process, and respond to visual images. These factors are examined in the following sections of this report.

SECTION III

THE PROCESS OF VISION

3.1 GENERAL

Human vision is a dual process which occurs partly in the eye and partly in the brain. Electromagnetic energy within the visible spectrum provides the stimulus, which is received by the eye and transferred to the brain where it is registered as a conscious sensation. The eye in some ways is similar to a camera: It has a lens through which the light rays are transmitted and focused and a sensitive area (the retina) upon which the light rays from the image fall. The retina is analogous to the film of the camera. The lens of the eye normally adjusts automatically to bring about proper focus of the image on the retina. Upon receiving light through the lens, the nerve receptors on the retina set up impulses which are transmitted through the optic nerve to the brain, where translation takes place and the image is perceived. The pupil controls the amount of the light that enters the eye. In bright light the pupil contracts; it dilates when the amount of light is reduced. The eyes are moved and directed by sets of muscles that surround the eyeballs. The eye's field of vision covers a wide angle of about 200 degrees horizontally and 130 degrees vertically. The binocular field of vision (seen by both eyes simultaneously) is approximately circular and about 130 degrees in diameter (ref. 3). In the center (foveal) region of this field the eye is responsive to color and detail, whereas in the outer (peripheral) region, it is primarily sensitive to intensity and motion. These visual fields are represented in figure 1.

3.2 VISION CONSTRAINTS

The limits of vision are chiefly determined by four factors: intensity threshold, contrast, visual angle, and time threshold (ref. 30).

Intensity threshold is the lowest brightness level that can stimulate the eye and is dependent upon the recent exposure of the eye to light. If a person goes from a brightly lighted area to a darkened area, it may take an hour for the eye to reach maximum sensitivity. When he goes from a darkened area to a brightly lighted area the adaption time is much shorter and may be only a matter of minutes.

Contrast represents a difference in the degree of brightness or intensity. The limit of vision with respect to contrast is the least brightness difference that can be perceived. The eye is sensitive to percentage changes rather than absolute changes in intensity.

If an object under view is made smaller or the distance from which it is viewed is increased, the angle formed by the light rays from the extremities of the object to the eye becomes smaller. The angle subtended by these rays to the eye is referred to as the visual angle. This angle must be sufficiently large to project on the eye's retina an image of sufficient size to allow detection and resolution of detail. If the image is reduced in size, a point will be

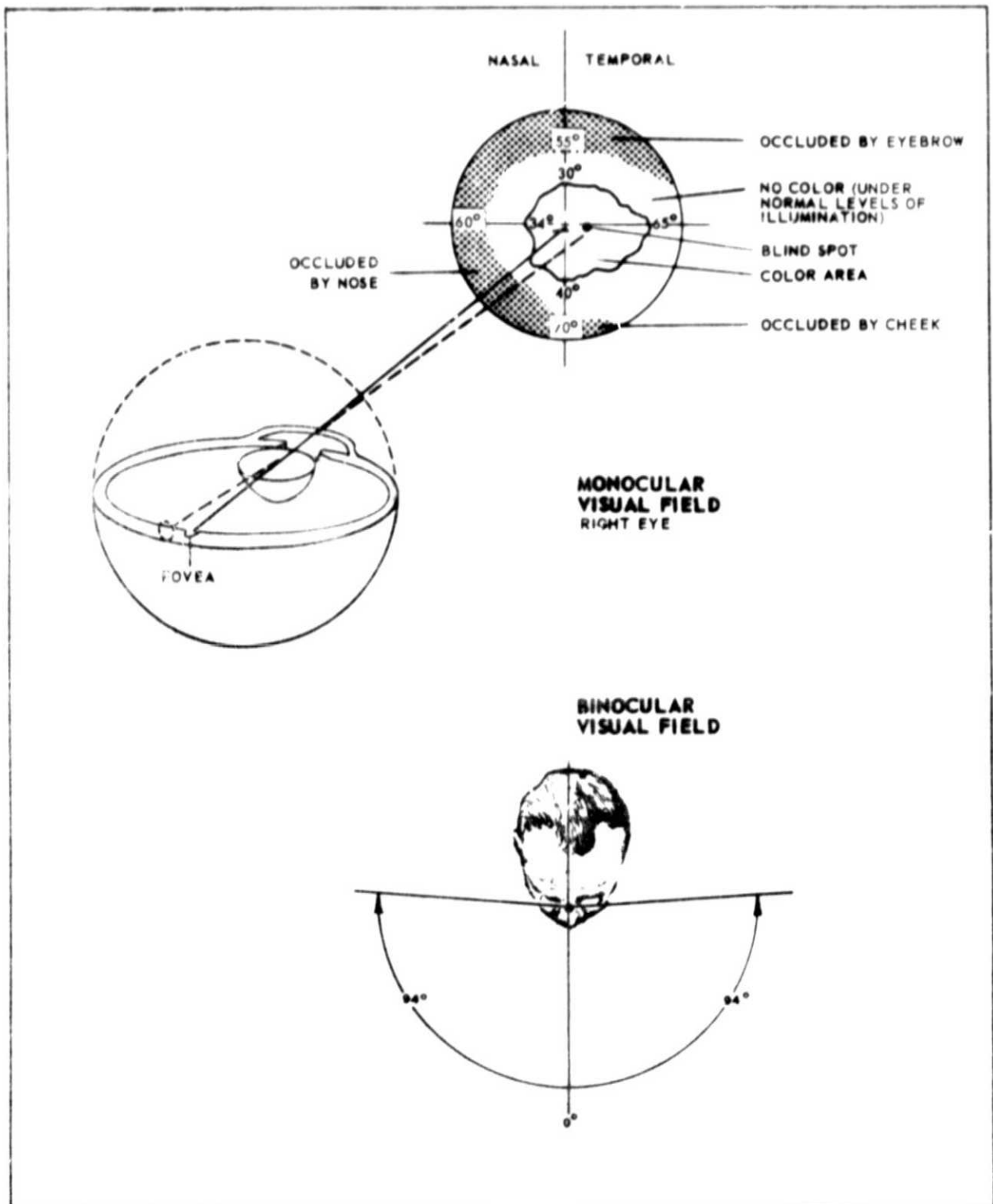


Figure 3-1. Visual Field

reached where the eye can no longer detect the object. The minimum visual angle is not only dependent on the size of the object but also upon the contrast and brightness of the image; for example, an object having sharp contrast could be distinguished at a narrow visual angle while the same size object having a lower contrast might not be visible. The same applies to brightness change; i.e., a very small object can be more easily seen at a high brightness level than at a low brightness level. A quantitative analysis of the importance of visual angle will be discussed further in the following sections.

Time threshold is the minimum time during which a stimulus must act in order to be effective. If the exposure period is too short, the rods and cones of the eye do not have time to respond to an image on the retina. The time threshold is dependent upon size, brightness, and color of the object.

3.3 THE MECHANISM OF COLOR PERCEPTION

Radiant energy reflected or transmitted by an object forms an inverted image on the eye's retina. The light-sensitive neural receptors in the retina are called rods and cones. There are approximately 6 to 7 million cones in the eye, predominantly in the center (foveal) region of the retina. There are about 130 million rods, generally predominant toward the outer reaches of the retina around the sides of the eyeball. There is no clear-cut separation between the sections in which the rods or cones predominate. The rods are primarily sensitive to the amount of light and movement rather than differences in color. They respond to extremely small amounts of light and give us the ability to see at nighttime or under conditions of low light levels.

The cones in the retina have a more complicated response than the rods. Instead of simply detecting light and dark and giving us a series of grays, they also provide our perceptions of chromatic color. That is, by cone vision we can see yellow-blue differences and red-green differences. The cones are quite abundant in the foveal pit where there are no rods, and are quite plentiful up to 5 degrees from the center (parafoveal region) where only a few rods are intermingled. There are also a very few cones mixed with rods in the extreme periphery of the retina only; these enable us to see from the corner of the eye. In the center of the retina the very closely packed cones permit the perception of fine detail; the visual angle for which we have the best resolution of detail and color perception is on the order of 2 to 2.5 degrees (foveal vision or cone vision).

SECTION IV

VISION FACTORS

4.1 GENERAL

The vision factors considered here relate to the responses of the human eye to radiant energy within the visible spectrum. Only those factors considered most relevant to the comparison of color and monochrome displays are discussed in detail. These include sensitivity, selectivity of the eye to radiant energy, brightness and contrast, field of vision, acuity and resolution, and time responses.

Some other vision factors such as adaption, convergence, movement, peripheral vision, and scotopic and mesopic vision are omitted because they are not considered limiting factors for the purpose of this study. These factors would be of considerable importance in the design of radar or aircraft display systems where environmental and ambient conditions are less easily controlled than for ground-based information displays.

4.2 SENSITIVITY

The sensors in the human eye are the rods and cones distributed on the surface of the retina. The rods perceive only black, white, and shades of gray. The cones, above a very low minimum intensity of illumination, permit color perception.

When the illumination is above approximately 0.01 lm/ft^2 , the photopic (cone) system of vision is used; when it is below approximately 0.001 lm/ft^2 , the scotopic (rod) system is used. Illumination between 0.01 and 0.001 lm/ft^2 establishes a condition to which both systems respond; we use this "mesopic" vision at twilight and dawn, when we can see color in the sky, but see objects on land only in shades of gray (ref. 55).

The eye is sensitive to radiant energy in the spectral range of approximately 380-750 nm; all wavelengths within this range are effective in stimulating the retina. As light levels are decreased the relative luminosity of colors changes because of a gradual transition from cone to rod vision and the fact that sensitivity of rods and cones to the wavelengths of the visible spectrum differs, as shown in figure 4-1. In this figure the ordinate is the reciprocal of the energy which is just visible for each wavelength of light (scotopic vision) or which matches moderately bright standard light (photopic vision). The curves are adjusted to a common scale by making the maximum of each curve equal to one.

An information display system operating in a ground-based environment can have controlled ambient lighting conditions and displayed-image brightness of sufficiently high level that the observer would be using photopic vision. This

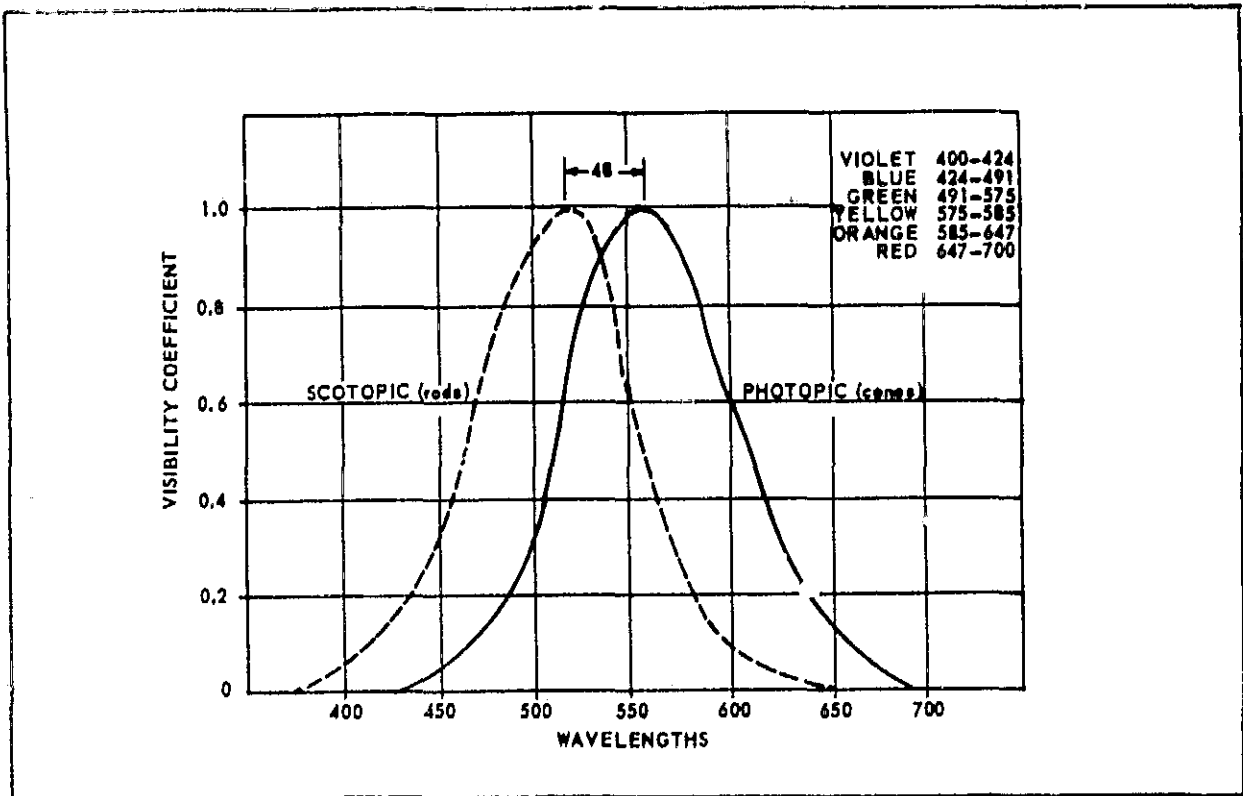


Figure 4-1. Relative Spectral Sensitivity of the Rods and Cones
(From Reference 55; See Note)

NOTE

Rod vision (dotted curve) serves us in very dim light, such as starlight; cone vision (solid curve), in daylight. The solid curve refers only to the light-dark aspect of daylight vision and is called the relative luminosity curve.

means that primarily the cone system would be functioning and the operator would have good color perception and visual acuity if brightness levels, target size, color and contrast were properly selected.

4.3 SELECTIVITY

Persons with normal trichromatic vision can match 160 or more distinguishable different hues by mixing three independent adjustable primary colors, such as red, green, and blue (ref. 55). However, when we try to identify specific

colors within the visible spectrum on an absolute basis the number of identifiable colors is reduced considerably. The number of easily identifiable colors depends on luminance, size (in visual angle), and color of the light source (lights). Figure 4-2 shows 10 spectral colors that can be identified with 2 percent error after a relatively short training period when lights have a luminance of 1 mL or more. The angular subtense of the color source should not be less than 15 minutes of arc for highly accurate color recognition (ref. 56). However, for both speed and accuracy of recognition, in practice the number of colors used for coding applications should be limited to no more than five when absolute color identification is required.

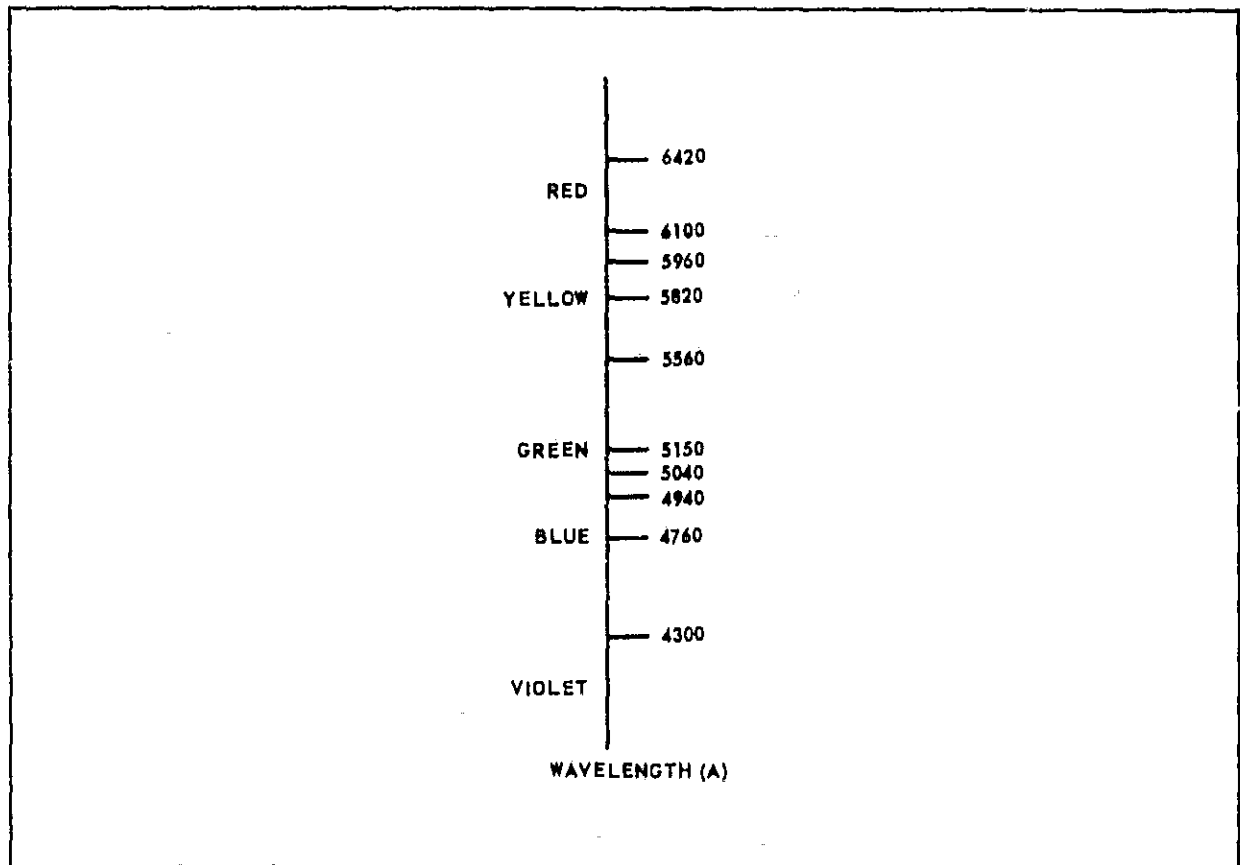


Figure 4-2. Spectral Colors (From Reference 56)

4.4 BRIGHTNESS AND CONTRAST

In the design of imaging displays such as radar or television a wide dynamic range of intensity levels is required (to allow detection of small weak targets in radar and to provide good scene rendition in television). Hence, for these

applications contrast range is extremely important. However, for information systems two levels of intensity are of primary concern: Usually a high level of brightness when the symbol is to be displayed and a low level when it is not. Intermediate intensity levels are not important unless intensity coding is employed.

Brightness and contrast of displayed information in relationship to ambient lighting conditions is still a significant design factor for information display systems. The major consideration in comparing color and conventional black-and-white display is the ambient lighting level. With conventional color CRT display devices, the brightness of the spectral colors is lower than can be obtained with a monochrome CRT; therefore the system must be operated in a lower ambient lighting environment. Reference to figure 4-1 shows that this problem is aggravated at the red and blue ends of the visible spectrum due to the normal eye response.

Up to a certain level, visual acuity is increased by luminance contrast. Making the target or displayed information of different colors does not increase acuity if there is high luminance contrast. However, if luminance contrast is low, color contrast improves visual acuity appreciably (ref. 56).

4.5 FIELD OF VISION

The ability of the average normal human to correctly perceive color is dependent on many factors, chief among which are size of target, brightness, color, and time of exposure.

The size of the target determines the visual angle and the resultant image size appearing on the retina. The limits on the field of vision where color is correctly perceived can be estimated by reference to figures 3-1 and 4-3. Figure 4-3 shows that the eye perceives only white light in the peripheral area of the retina and vision becomes dichromatic in a peripheral zone at approximately 50 degrees from the fovea. (It should be noted that the boundaries of trichromatic, dichromatic and monochromatic zones of the normal retina are not sharp as the figure indicates. The zones can vary from individual to individual in terms of both angle and sensitivity to color.) Although not indicated in the figure, the eye becomes tritonoptic (lacking blue sensitivity) when a field size of given brightness subtends a visual angle of approximately 15 minutes of arc or less. This limitation will tend to establish the minimum size of a displayed image when absolute color identification of all hues is necessary.

In general, the eye cannot perceive color of very small objects or areas. If colored objects under observation are gradually reduced in area all sense of color disappears long before the geometric detail of the area or object is lost. Eventually all objects appear to become black and white objects; colors appear to change to gray or white or black, but retain their definition for a long time. When image dimensions are reduced, blue images lose their definition first, then red images, and finally green images (ref. 30).

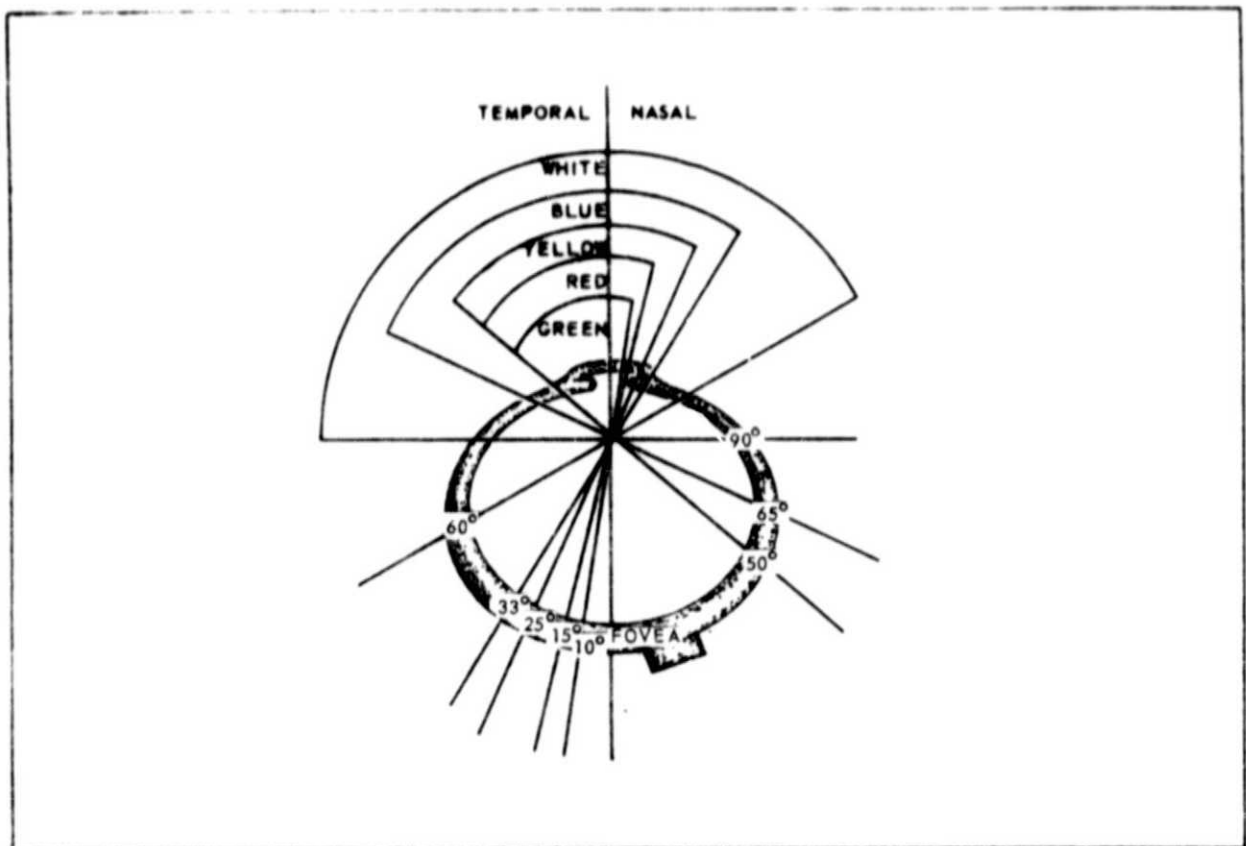


Figure 4-3. Sensitivity Zones (From Reference 55; See Note)

NOTE

Not all zones of the retina are equally sensitive to color. Toward the periphery, objects can still be distinguished while their color cannot. Some colors are recognized at greater angles away from the fovea than others. The accompanying figure shows the limits of the retinal zones in which the various colors can, under normal illumination, be correctly recognized.

4.6 VISUAL ACUITY

The resolution of the display system is a very important design parameter since it impacts heavily on the ability to recognize and correctly identify displayed information. If resolution is poor, reading errors can become excessive and identification time may be prohibitively long.

The smallest detail that the eye is capable of resolving at a specified distance is referred to as minimum visual acuity. Visual acuity is expressed by the visual angle in minutes of arc, or as the reciprocal of this angle. The normal human eye has a minimum separable acuity of 1 where it can detect a gap (element) of about 1 minute of visual angle at ordinary, indoor levels with targets of a high luminance contrast. In general, visual acuity is a function of brightness levels, contrast, and background brightness. Curves showing the relationship for visual acuity as a function of these parameters are given in references 29 and 56.

Color of the observed target has some effect on visual acuity. Normally, visual acuity is given for white light. With monochromatic light, the acuity is very slightly higher for the yellow and yellow-green wavelengths and slightly lower for red wavelengths. In blue (or red) light, visual acuity may be 10-20 percent lower, and in violet light the reduction in visual acuity is 20-30 percent (ref. 3).

The above limit of visual acuity tends to establish the criterion for resolution capabilities required of a display system. When necessary, the display should be scaled so that detail resolution subtends at least 1 to 2 minutes of arc to the observer's eye.

References reviewed indicate that when alphanumeric symbols are displayed in black and white, the displayed character should subtend a visual angle of 10 minutes of arc for near-threshold conditions. However, for good legibility and highly accurate reading the character should subtend a visual angle of 15-20 minutes of visual angle (ref. 29), and 30 minutes may be required to accommodate persons with subnormal acuity.

4.7 TIME RESPONSE

If a colored light source is turned on for a very short period of time the color may not be accurately perceived by the observer. The minimum time of exposure depends on many factors and cannot be stated quantitatively. However, we know from experiments that color can be perceived for exposure times as small as 100 milliseconds with adequate brightness level. For the purpose of this study it is assumed that the display device used in an information display system (such as CRT) would have adequate persistence and the image would be repetitively displayed (at a rate above the critical flicker frequency) to give a continuous image of average brightness.

The sensation of flicker is determined by the persistence of the eye. The threshold of flicker perception (also known as the critical frequency) for any particular observer is a function of refresh rate, brightness, color, size of illuminated area, ambient light, surrounding surface, persistence of phosphor, angle of vision, and movement of displayed data. The design procedures for a flicker-free display would be essentially the same for a color display system as for black-and-white systems. For example, a flicker-free display at 50 fL brightness would be expected to have a refresh rate greater than 47 Hz. (For further discussion on critical flicker frequency, see reference 29.)

For light levels where cone vision is operative, the color of the flickering source has essentially no influence on the critical flicker frequency (references 29 and 8). Hence, we may conclude that the use of color would not adversely affect display rates or present objectionable flicker problems.

SECTION V

COLOR VISION DEFECTS

5.1 GENERAL

A review of literature relating to the use of colors in display systems shows considerable emphasis on operational problems resulting from inadequate screening of personnel for color-vision defects. Much of this literature reflects results of investigations and research related to the use of color displays by pilots operating in high-performance aircraft. This concern is justified by the critical nature of the overall mission requirements and the complex mission tasks performed. Our interest here, however, is to determine whether and to what extent the same concern and criteria apply when using a color display as the interface between the computer and the human in a ground-based interactive information display system. To make a proper assessment of this problem it is necessary to define the nature and extent of color-vision defects and then to relate these data to the use of colors in a ground-based information display system environment. Results of this investigation are stated in the following sections and summarized in tables 5-1 and 5-2.

5.2 NORMAL COLOR VISION

Based on current theories, normal color vision is a three-dimensional phenomenon where a person with normal color vision specifies a stimulus as a color in terms of its equivalence to a three-part mixture such as a mixture of three amounts of red, green, and blue light. People with normal color vision may differ considerably in their ability to make fine color distinctions, but this is a matter of degree, not in the kind of color discrimination. A person who has normal color (trichromatic) vision is referred to as a trichromat. Most people have normal color vision; only about 8 percent of the healthy male population and 0.4 percent of the female population have some form of color vision defect (ref. 6).

5.3 ANOMALOUS TRICHROMATS

While trichromats are considered to have normal color vision, there are color-weak individuals among them whose impairment may be so slight that only very sensitive tests will reveal it. The largest proportion of color-deficient people have a type of color weakness called anomalous trichromatism and are referred to as anomalous trichromats. Though resembling normals in that they require three primary colors to match spectrum colors, they may need them in abnormal amounts. Anomalous trichromats are primarily of two types called protanomalous and deuteranomalous. Figures 5-1 and 5-2 show the relative luminous efficiency of the observer as a function of wavelength of equal-energy stimuli. In figure 5-2, note that the luminosity functions of protanomalous observers, like those of the protanope, seem to be deficient at the long-wave end of the visible spectrum. The deuteranomalous observers, on the other hand, have luminosity functions well within the variations shown by

Table 5-1. Classification and Characteristics of Color Vision Defects

Type	Visual Characteristics
TRICHROMATS (Require three primaries to match all colors)	
Normal	Normal light/dark, yellow/blue, and red/green discrimination
Protanomalous	Weak red/green discrimination; requires more red stimulation
Deuteranomalous	Weak red/green discrimination; requires more green stimulation
Tritanomalous	Weak yellow/blue discrimination; requires more blue stimulation
DICHROMATS (Require two primaries to match all colors as they see them)	
Protanopic	Light/dark and yellow/blue discrimination; red/green confusion and loss of brightness resulting from lack of red cones.
Deuteranopic	Light/dark and yellow/blue discrimination; red/green confusion resulting from lack of separate red and green cones.
Tritanopic	Light/dark and red/green discrimination; no blue cones (The normal observer exhibits tritanopia when the field of vision is limited to the fovea centralis, which contains no blue cones)
MONOCHROMATS (Can match only in terms of shades of gray)	
Congenital	Light/dark discrimination only. "Cone blindness" associated with poor daytime visual acuity.
Acquired Monochromatism	Light/dark discrimination only, but may have good day and night visual acuity.

observers with normal trichromatic vision. Although quite rare, there are also tritanomalous trichromats who require more blue stimulation than the normal observer.

Table 5-2. Frequency of Occurrence of Color Defects
(From Reference 6 and Others)

Type of Defect	Percentage of Population Affected	
	Males	Females
Protanomaly	1.0	0.02
Deuteranomaly	4.9	0.38
Tritanomaly	RARE	RARE
Protanopia	1.0	0.02
Deuteranopia	1.1	0.01
Tritanopia	0.002	0.001
Congenital Total Color Blindness (Cone Monochromats)	0.003	0.002

5.4 DICHROMATS

The next most common form of color deficiency is dichromatism. Observers with this deficiency are capable of making color distinctions of only two kinds: one achromatic (light-dark) and one chromatic (either yellow-blue or red-green, usually the former).

To an observer having red-green blindness the short-wave end of the spectrum appears blue, the long-wave end yellow. These two bands are separated by a region at about 495 nm which, like average daylight, has no hue at all and is called the neutral point. From zero at the neutral point the saturations of the spectrum colors increase toward both the long-wave and the short-wave ends. For these types of vision, as for normal vision, the equal-energy spectrum colors also become progressively less bright as the ends of the spectrum are approached.

There are two subtypes of red-green blindness, one characterized by abnormally low luminosity of the long-wave portion of the visible spectrum, the other by essentially normal luminosity function (ref. 6).

Red-green blindness with abnormally low luminosity of the long-wave end of the spectrum is called protanopia. The name for red-green blindness with substantially normal luminosity function is deuteranopia (see figure 5-1). A protanope

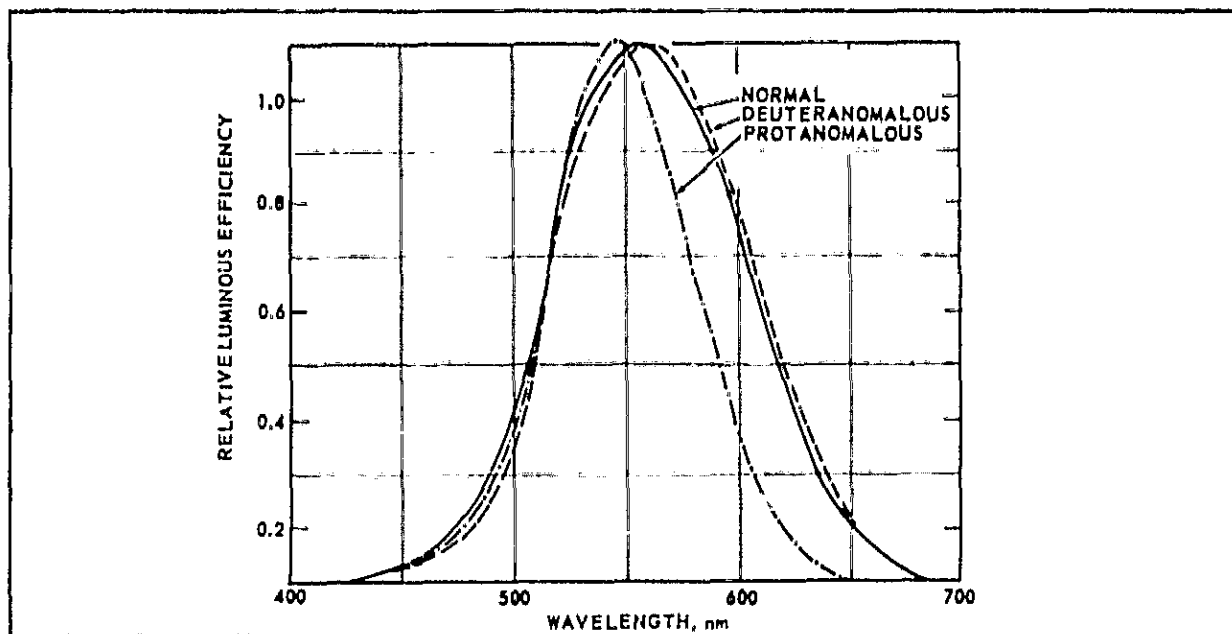


Figure 5-1. Mean Relative Luminous Efficiency Curves for the Normal Trichromat, the Protanomalous and the Deuteranomalous Observer (from Wright 1946)

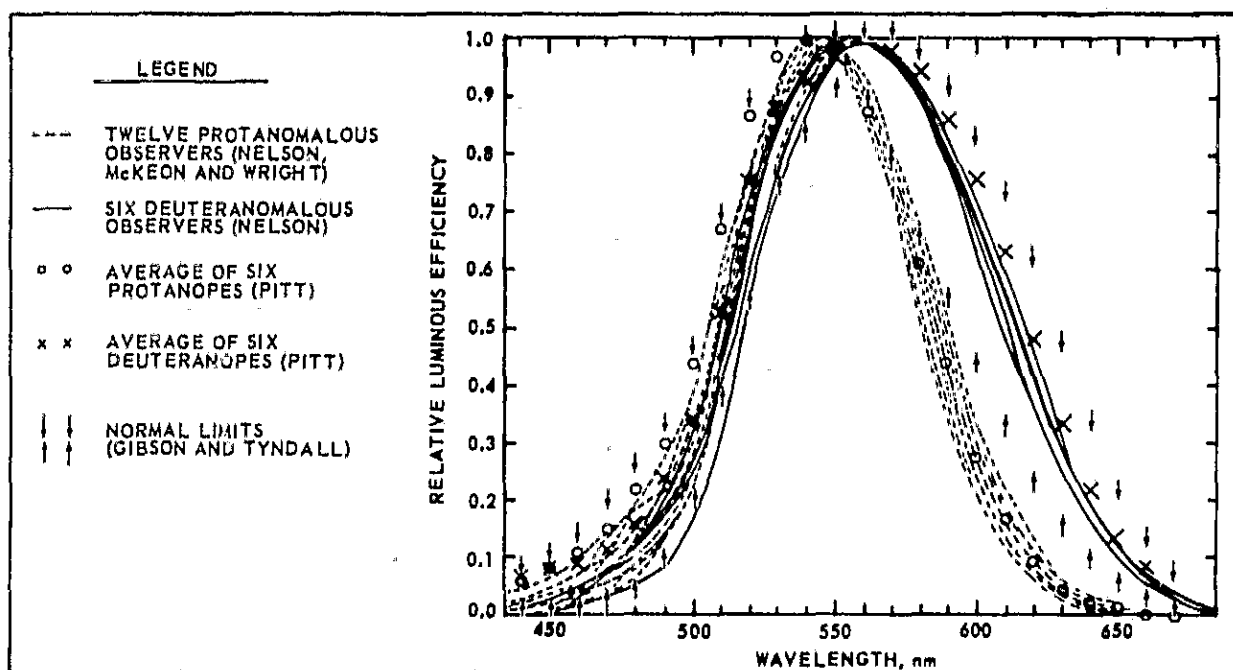


Figure 5-2. Relative Luminous Efficiency for Normal and Color-Defective Observers, Showing Individual Variations

confuses red and bluish green with gray and with each other. The deuteranope confuses purplish red and green with gray and with each other.

Dichromatic vision may also take the form of yellow-blue (more precisely greenish yellow and purplish blue) blindness, called tritanopia. For this type the luminosity function is nearly normal. The spectrum appears red at the long-wave end, becoming more and more grayish as the neutral point (at about 570 nm) is approached. On the short-wave side of the neutral point the hue perceived is green or bluish green with saturation increasing up to about 470 nm, then decreasing toward zero as the short-wave end of the spectrum is approached. Some tritanopes have a second neutral point near the short-wave end (430 nm and lower); others see green or bluish green of diminishing saturation as far down in wavelength as they can see anything at all. A tritanope confuses bluish purple and greenish yellow with gray, and with each other. Tritanopia often occurs as a result of inflammation or detachment of the retina but is rarely congenital (ref. 6).

5.5 MONOCHROMATS

The least common form of color defect is monochromatism. Observers with this type of defect are called monochromats and are the truly color-blind persons. Such observers can make only one kind of color discrimination--light-dark--and no chromatic discrimination whatsoever. Observers with this deficiency see only in terms of shades of gray. Acuity is usually poor in monochromats; their vision approximates black-and-white photography with poor definition. However, some monochromats do have good visual acuity.

5.6 ACQUIRED COLOR BLINDNESS

The forms of color vision defects previously discussed have been found in persons without previous history of disease in the eye or optic nerve and are considered congenital defects for which there is no known cure. In contrast, color blindness can be acquired by an individual who previously has had normal color vision. Some of the acquired defects can be cured, depending on the type and the manner in which it was acquired. In many cases acquired color blindness is accompanied by less than normal visual acuity. Some of the causes are disease affecting the retina, the optic nerve, or the optic cortex in the occipital lobe of the brain. Toxic agents and poisons as well as tobacco and alcohol can cause color vision defects with the latter two being the most common agents producing impairment of vision (ref. 6).

5.7 CONDITIONS AFFECTING NORMAL COLOR VISION

Observers with normal trichromatic color vision can exhibit the characteristics of a color-deficient observer under certain abnormal conditions involving insufficiencies of field of vision, size, luminance, or time.

When vision is present in the retinal regions somewhat removed from the fovea, it resembles that of the deuteranomalous observer, as do the early stages of progressive red-green blindness. Vision is dichromatic in a peripheral zone 25 to 40 degrees from the fovea; in the zone more than 40 degrees from the

fovea vision is very much like acquired total color blindness. The boundaries between the trichromatic, dichromatic, and monochromatic zones of the normal retina are not sharp. Their exact locations depend upon the size and luminance of the test field and the surroundings (ref. 6).

With a sufficient reduction in size, in an area of given luminance perceived in the foveal and parafoveal region, the observer may fail to experience yellow-blue distinctions, although red-green and light-dark distinctions can still be easily made. For field sizes of about 15 minutes of arc, the normal retina responds like the tritanopic eye. Color discrimination is greatly reduced if the observer stares at the color field for a prolonged period of time. Further reduction of that area can cause the area to fail even to show red-green distinctions, although light-dark distinctions can still be made, i.e., the normal trichromatic foveal and parafoveal regions become monochromatic (ref. 6).

When the luminance of the area is insufficient, the normal dark-adapted eye responds to weak stimuli in every way like that of the congenitally total color-blind. If the luminance is sufficient for cone vision, chromatic differences can be perceived.

If a luminous area is presented to the light-adapted eye for an insufficient period of time, it will be perceived as a flash and no chromatic color will be experienced. Under these conditions, the normal eye makes light and dark discriminations only and the observer's vision resembles total color blindness (ref. 6).

5.8 ASSESSMENT OF THE IMPACT OF COLOR BLINDNESS ON THE USE OF COLOR DISPLAYS WITH INFORMATION SYSTEMS

As previously noted, pilots operating high performance aircraft and conducting complex missions are carefully screened for color defects. Color perception and discrimination are necessary to make fine color distinctions during reconnaissance missions and instantaneous identification of targets. The pilot operates in an environment of ambient lighting levels that vary from extreme bright direct sunlight to low levels where the eye is completely dark-adapted. He must be able to identify colored light beacons of low intensity viewed from distances which subtend an extremely small angle of vision. He must also view color-lighted instrumentation panels. In addition to good color perception ability he must have extremely good visual acuity and visual time responses. In general, he cannot have any significant visual defects including color defects. Hence, careful screening of pilots is completely justified, even though some color-weak individuals are rejected whose color perception may be acceptable under ideal viewing conditions such as is possible with some anomalous trichromats.

The environmental and viewing conditions applicable to colored displays in an information system are not nearly so stringent as for the pilot operating high performance aircraft. If we use a color CRT as the display device, the viewing conditions can be carefully controlled by proper design of the system. Within limits the ambient conditions, brightness, hue, saturation, and target area

can be controlled and selected to accommodate most color-deficient observers, especially the anomalous trichromats. If colored light sources are to be used for coding, and if color-blind people will have to use the color code, there are only three colors that should be used. These three colors are aviation red, aviation green, and aviation blue as defined by the Army-Navy Aeronautical Specification AN-C-56 (ref. 56). Also, white or yellow should not be added to the code because color-blind people confuse red with yellow and green with white. If the display system is designed for use by persons with essentially normal color vision, the number of colors used in the display could be as high as 10. In practice the number of colors is normally restricted to five.

Another factor that must be considered is the number of potential viewers having visual color defects. Table 5-2 indicates that approximately eight percent of the male population have some form of color defect. Of these, approximately six percent are anomalous trichromats with the least severe form of color defect. The proper design of a color CRT display with proper choice of colors, sufficient intensity, and sufficient image area would accommodate many anomalous trichromats. The remaining two percent are the dichromats and monochromats with the dichromats predominating. To design the display system to accommodate the dichromats would impose severe constraints and the advantages of a color display system could not be fully exploited.

5.9 CONCLUSIONS

Color vision defects should not be an overriding factor influencing a decision to use color displays in information systems. Proper choice of ambient conditions, color, brightness, viewing distance and image area could accommodate the major portion of color-deficient observers of the anomalous trichromatic type. If this group is a representative sample of the male population, only about 50 percent would have extreme difficulty in performing tasks when color displays are used. When the operator is required to perform critical tasks based on observed information, he should be screened for color blindness as well as other vision defects such as poor visual acuity. Screening tests could be much less stringent than those used for screening pilots. For color displays used with information systems, it would be necessary to identify only the monochromats, dichromats and the seriously afflicted anomalous trichromats. This screening procedure could eliminate approximately three to five percent of the operators needed to perform critical tasks.

SECTION VI

THE PSYCHOLOGICAL ASPECTS OF COLOR

6.1 GENERAL

Color can mean many things; it may mean a certain kind of light and its effect in the mind of the viewer. It is much more than something physical. The color we see is the result of the physical modification of light in the use of colorants or the wavelengths of light sources as observed by the human eye (a psychophysical process) and interpreted in the brain (which introduces psychology).

We can with some degree of certainty predict and measure the effects of color on the performance of an average observer in physical terms, such as his ability to perceive and resolve colored images. However, when we try to quantify or qualify the psychological aspects of color vision we find there is little significant knowledge available that could rigorously support the use of color in an information display system. Psychological experimentation has shown that color does influence the mental and physical states of the human observer. The psychological association of color in the human mind can produce changes in mood and cause sensations of temperature changes and of apparent distance. Experimentation has also shown that color does have aesthetic value and that people have color preferences, which, however, vary considerably among individuals.

There are several known psychological observations that should be considered as possible factors affecting the performance of an observer viewing an information display system. These factors are the attention-getting qualities of color, the association of color with well-learned physical states or conditions (e.g., red means danger and green means safe), speed and ease of learning and comprehension, and speed of recognition for contrasting colors.

6.2 THE ATTENTION-GETTING QUALITIES OF COLOR

The fact that color has attention-getting qualities has been strongly confirmed by psychological investigations. Human beings exist in the midst of a complex of stimuli to which they may or may not respond. From all of the energies about us, our sense organs are responsive to only certain ones. However, the selectivity of the human organism goes far beyond mere sensitivity or insensitivity in the sense organs. There is not only a sensory but a psychological selectivity--an emphasizing or ignoring of responses to certain stimulus patterns--which varies from time to time and which does not result only from changes in the sense organs. Although several stimulus patterns compete, only those fitting the need of the moment are selected. When a person selects certain stimuli from all those in his environment, and responds mainly to them, he is said to be giving them his attention. Attention may also be regarded as a "set" or a readiness to respond in a selective way to some stimulus situation which permits a variety of responses. For example, a person conditioned with

apriori knowledge of the appropriate response or action to be taken when a certain colored image appears would respond accordingly. His motivation would determine which particular stimulus will win his attention. Changes of color also attract attention. Some stimuli are more potent in attracting attention than are other physically stronger ones, even in the absence of previous experience and conditioning -- for example, saturated colors over pastel shades (ref. 7).

6.3 ASSOCIATION OF COLORS

Throughout our lives we have either consciously or unconsciously associated color with certain states, conditions or events. We usually associate the color red with dangerous or hazardous conditions and the color green with safe conditions. We are so familiar with the use of these colors that the human response is essentially instantaneous. Through a program of training and conditioning, an observer could develop the same sensitivity to other colors, thereby reducing the stimulus-to-response-time interval.

6.4 SPEED AND EASE OF LEARNING

Little information is available to support the proposition that color should be used because its use expedites learning. However, we can assume that the attention-getting qualities of a color or change in color as well as the association aspects are conducive to more efficient learning.

Colored process displays are used extensively throughout industry and academic institutions in training and demonstration programs. In these displays comprehension is enhanced considerably through the use of color contrast and color changes to identify functions, changes in state, and flow processes. This assessment is based on comparisons of color and black-and-white process displays.

6.5 SPEED OF RECOGNITION

Experimental results have shown that color-coded qualitative information can be identified in less time and with greater accuracy than with other commonly used methods of coding. This is primarily true when information is displayed in a random format and display density is high.

6.6 CONCLUSIONS

The psychological aspects of color vision are somewhat controversial and difficult to support with rigor. However, sufficient experimental results are available to indicate that the use of color in an information display system could improve operator performance in terms of speed, accuracy and comprehension for such applications as identification of group or class data, comprehensive understanding of process systems performance, and situations where the operator must react quickly to dangerous or hazardous conditions as indicated on his display. The last item assumes that corrective action would be under the control of the operator rather than the computer, which could automatically take corrective action.

SECTION VII

COLOR CODING

7.1 CLASS CODING

Experiments show that color coding is very effective in providing display operators with a means for differentiating among classes of data.

The time required for an operator to find a particular item of random location on his display is essentially a linear function of his display density; tripling the amount of displayed data will triple the time needed to locate any one item. If the displayed data is color-coded according to the data class to which it belongs, search time becomes proportional to the data density of the particular class to which the sought item belongs. Another useful application of color coding is class counting, where all items in a given class must be found or counted. The time required to execute class counting and the attendant errors increase as display density grows. By encoding displayed data in five colors, counting time can be reduced by 50 to 70 percent below the corresponding value for a single color display. In addition to improved counting time performance, counting errors are reduced by a factor of approximately 75 percent (ref. 66). Since five colors are so effective in improving operator performance, one might expect that by using more colors even greater improvements could be obtained. Unfortunately, this is not possible. When comparing the color against another, the average person with normal color vision can distinguish a great many colors. When colors are presented singly without any reference, only 10 colors can be recognized consistently, even under ideal viewing conditions. Under practical viewing conditions, probably no more than five colors should be used if reliable color identification is required.

Color coding effectively decreases search and counting time since it provides good contrast between data classes and between the data and the background. No other coding technique has proven as successful in providing visual separability among randomly displayed data with high display density. The eye-and-brain combination seems able to recognize colors at a glance while recognition of other codes demands a more detailed examination of the data. Display density can be effectively reduced by using color to encode data classes and by restricting the use of other codes. The display operator is able to treat all items not of the color of interest as background data that can be safely ignored for the moment (ref. 66).

Quantitative results of various experiments (references 28, 68, and 69) show the advantages of color coding over other common forms of coding and the large reduction of search time when color coding is used. Although some of these experiments were directed toward aircraft display systems and not specifically for CRT information display systems, we can assume that color coding would provide essentially the same advantages for systems using a CRT if the tube were large enough to accommodate the display of high density information.

7.2 QUANTITATIVE VS. QUALITATIVE DATA

Color coding is effective for coding quantitative information only when the number of states or possible values is small, as for binary values (e.g., green equals "1" and red equals "0"). However, if the same colors are used to represent different values for other measured parameters there would be considerable confusion which could slow down the reading rate and decision process and increase the number of errors made by the operator. Hence, in general, color coding is not suitable for coding quantitative information.

The most desirable method of coding quantitative information is by the use of numerals and letters where the number of levels which can be discriminated on an absolute basis is unlimited; little display area is required if there is good contrast and resolution.

7.3 MULTIDIMENSIONAL CODING

If information displayed on the face of a CRT is in the form of color-coded alphametrics we have a two-dimensional code. The alphametrics are used to display quantitative information and the color of the particular alphametric displayed can give qualitative information about its state, tolerance value, urgency, class, or any other qualitative meaning assigned to its particular color. Another approach would be to have all displayed alphametrics in black and white and to color-code the background to obtain the qualitative information.

By using multidimensional coding as suggested above, we take advantage of the merits of each form of coding, i.e., the alphametric code gives the necessary accuracy for the display of quantitative information while the color coding, if properly used, reduces recognition and search time. The use of color, in effect, provides an additional coding dimension.

7.4 INFORMATION CONTENT

Color coding can be used effectively to increase the information content of a displayed symbol or a group of symbols. As a simple example, consider a 1/4-inch square symbol with fixed position and orientation displayed on a CRT. If this symbol is displayed in monochrome, it can have two probable alternatives--black or white. Then for equally probable alternatives, the amount of information; n = number of equally probable alternatives or $H = \log_2 2 = 1$ bit for black and white. If encoding is used with four colors (red, blue, green, and yellow) then for the same square symbol, the amount of information would be $H = \log_2 4 = 2$ bits.

This demonstrates the possibility of increasing the information content of a given symbol with fixed size, position, and orientation by using color coding. The same results could be achieved using monochrome if four different intensity levels were used instead of four different colors. However, without a reference for comparison of intensity levels, intensity coding is less reliable than color coding. The number of intensity levels that can be discriminated on an absolute basis is 4 or 5, while 9 or 10 different colors can be discriminated on the same basis. Table 7-1 gives a comparison of the various coding

Table 7-1. Amount of Information in Absolute Judgments
of Various Stimulus Dimensions

Sensory Modality and Stimulus Dimension	No. of Levels Which Can be Discriminated on Absolute Basis	No. of Bits of Information Transmitted (H) (Approx.)
Vision: Single Dimensions		
Pointer Position on Linear Scale	9	3.1
Pointer Position on Linear Scale Short Exposure	10	3.2
Long Exposure	15	3.9
Visual Size	7	2.8
Hue	9	3.1
Brightness	5	2.3
Vision: Combinations of Dimensions		
Size, Brightness, and Hue*	17	4.1
Hue and Saturation	11-15	3.5-3.9
Position of Dot in a Square	24	4.6
Audition: Single Dimensions		
Pure Tones	5	2.3
Loudness	5	2.3
Audition: Combination of Dimensions		
Combination of Six Variables**	150	7.2
Odor: Single Dimension	4	2.0
Odor: Combination of Dimensions		
Kind, Intensity, and Number	16	4.0
Taste:		
Saltiness	4	1.9
Sweetness	3	1.7

* Size, Brightness, and Hue were varied concomitantly, rather than being combined in the various possible combinations.

**The Combination of Six Auditory Variables included frequency, intensity, rate of interruption, on-time fraction, total duration, and spatial location.

methods and shows the levels that can be discriminated on an absolute basis and the corresponding information content in terms of bits.

7.5 CONCLUSIONS

Color coding can provide an effective means for improving operator performance in terms of speed, accuracy, and workload capacity for some applications.

Experimental results have shown that color coding is superior to other commonly used forms of coding for applications such as class counting and location of class information when displayed with random format with high display density. Also, it has been demonstrated that the use of color coding, in conjunction with other coding methods, can increase the information content of displayed data. The "attention-getting" qualities of color and speed of recognition make color coding effective for the identification of action items such as out-of-tolerance data and emergency situations.

Except for increasing the information content of a message, these advantages are the result of the fundamental idea that a person's visual mechanism and psychological and motor responses function in such a way that if he knows the particular color of immediate concern, his entire attention will be drawn immediately to the appearance of only that color and he will be able to treat all items not of that color as part of the background, thus restricting his attention and the area or portions of the display over which his eyes must scan.

Caution must be exercised in assessing the payoff or value of using color coding in an information display system. The benefits realized will depend largely on the nature of specific requirements and modes of operation. Maximum benefit will be realized when information is displayed in a random format, i.e., when the particular location of the measurement or data class is not precisely known and detailed search is required. At the other extreme, reduced benefit will be realized when information is displayed using highly structured format, in which the display operator has prior knowledge of where each measurements will appear on the face of his display. If the operator has no prior knowledge of the color to which a class belongs, then color coding will be of no value to him in reducing search or counting time.

The display of action items such as out-of-tolerance data and emergency situations is a good example of random format since prior knowledge of the state and location of a particular measurement is not known to the operator. Although there are many practical ways for identifying this type of information on a display, as by relocating out-of-tolerance data to a known position or area on the display device by computer manipulation, or by displaying such information on a separate display specifically designated for that purpose, color coding may be the most effective means for displaying this information because of its unique "attention-getting" qualities and simplicity of implementation. (The latter statement assumes that the information is one of the items being currently displayed. If a failure or out-of-tolerance condition is detected in the computer but does not appear on the display then the advantage of color coding is lost for the purpose of this comparison.)

REFERENCES

1. McCormick, E. J.: Human Engineering, McGraw-Hill Book Co., Inc., New York, 1957
2. Williams, C. S. and O. A. Becklund: Optics: A Short Course for Engineers and Scientists, Wiley-Interscience, New York, 1972
3. Smith, W. J.: Modern Optical Engineering, McGraw-Hill Book Co., Inc., New York, 1966
4. McCormick, E. J.: Human Factors Engineering, McGraw-Hill Book Co., Inc., New York, 1957, 1964
5. Morgan, C. T.; J. S. Cook, III; A. Chapanis; M. W. Lund: Human Engineering Guide to Equipment Design, McGraw-Hill Book Co., Inc., New York, 1963
6. Judd, D. B. and G. Wyszecki: Color in Business Science and Industry, John Wiley & Sons, Inc., New York, 1952, 1963
7. Ruck, F. L.: Psychology and Life, Scott, Foresman & Company, New York, 1948
8. Walsh, J. W. T.: Photometry, Dover Publications, Inc., New York, 1958
9. Horne, E. P. and M. A. Whitcomb: Vision Research Reports, National Academy of Sciences - National Research Council, Publication 835, Washington, D. C., 1960
10. Morris, A. and E. P. Horne: Visual Search Techniques, National Academy of Sciences - National Research Council, Publication 712, Washington, D. C., 1960
11. IEEE Transactions on Electron Devices, Publication of the IEEE Electron Devices Group, Volume ED-20, No. 11, November 1973
12. International Symposium, Digest of Technical Papers, Lewis Winner, New York, May 1971
13. International Symposium, Digest of Technical Papers, Lewis Winner, New York, 1972
14. International Symposium, Digest of Technical Papers, Lewis Winner, New York, 1973
15. Wohl, J. G.: Analysis of Man-Computer Roles in Prelaunch Fault Anticipation, Dunlap & Associates, Inc., Darien, Connecticut, 1965

REFERENCES (Cont)

16. Research on Man-Machine Relationships in Prelaunch Checkout of Advanced Space Vehicle, 570-OR-4, Dunlap & Associates, Inc., Darien, Connecticut
17. Anderson, R.; R. Bator; R. Gagan; J. Meads; L. Metrick: Interactive Specification of Data Displays, Prepared by Wolf Research & Development Corp., June 1970
18. Air to Ground Target Acquisition, AGARD Conference Proceedings No. 100, Technical Editing and Reproduction Ltd., London, 1972
19. Hopkins, A. and V. D. Hopkins: Human Factors in the Ground Control of Aircraft, AGARDograph No. 142, Technical Editing and Reproduction Ltd., London, 1970
20. Link, J. M. and L. L. Vallerie: Differential Thresholds for Motion in the Periphery, Dunlap & Associates, Inc., Darien, Connecticut, September 1969
21. Perry, I. C.: Nomenclature of Terrain Color, AGARDograph No. 159, Technical Editing and Reproduction Ltd., London, 1972
22. Recent Advances in Display Media, Symposium - Cambridge, Massachusetts, NASA SP-159, U. S. Government Printing Office, 1968
23. Bowen, H. M.; L. L. Vallerie; F. J. Affinito; J. G. Wohl: Apparent Movement Phenomena of CRT Displays, NASA CR 342, Dunlap & Associates, Inc., Darien, Connecticut, December 1965
24. Kleiman, E. B.: A Survey of Various Information Display Devices, Technical Report NAVTRADEVCEM, IH-74, (AD-653-867) Clearinghouse for Federal Scientific & Technical Information, May 1967
25. Botha, B. and D. Shurtleff: Studies of Display Symbol Legibility: Part II. The Effects of the Ratio of Widths of Inactive to Active Elements within a TV Scan Line and the Scan Pattern Used in Symbol Construction, Technical Document Report No. ESD-TDR-63-440, the Mitre Corp., Massachusetts, September 1963
26. Shurtleff, D.; M. Marsetta; D. Showman: Studies of Display Symbol Legibility: Part IX. The Effects of Resolution, Size, and Viewing Angle of Legibility, the Mitre Corp., Massachusetts, May 1966
27. Shurtleff, D. and D. Owen: Studies of Display Symbol Legibility: Part VI. Leroy and Courtney Symbols, the Mitre Corp., Massachusetts, May 1966

REFERENCES (Cont)

28. Colour Vision Requirements in Different Operational Roles, AGARD Conference Proceedings No. 99, Technical Editing and Reproduction Ltd., London, November 1972
29. Guidance and Control Displays, AGARD Conference Proceedings No. 96, Technical Editing and Reproduction Ltd., London, February 1972
30. Color - TV Training Manual, Howard W. Sams & Co., Inc., Indiana, 1956, 1965, 1970, and 1973
31. Toensing, R.: Graphic Displays for Process Insight, Control Engineering, April 1973, P. 47
32. Display for Approach and Landing of V/STOL Aircraft, AGARD Advisory Report No. 51, Technical Editing and Reproduction Ltd., London, November 1972
33. Vallerie, L. L.: Peripheral Vision Displays, NASA CR-1239, Dunlap & Associates, Inc., Darien, Connecticut, December 1968
34. Lyon, Jr., H. B.: AGARD Advisory Report No. 43, Technical Evaluation Report on 13th Symposium of the AGARD Guidance and Control Panel on Guidance and Control Displays, Printed by Editing and Reproduction Ltd., London, March 1972
35. Shurtleff, D.: Design Problems in Visual Displays: Part I. Classical Factors in the Legibility of Numerals and Capital Letters, AD-636-414, the Mitre Corp., Massachusetts, June 1966
36. Kosmider, G.: Studies of Display Symbol Legibility: Part V. The Effects of Television Transmission on the Legibility of Common Five-Letter Words, AD-633-261, the Mitre Corp., May 1966
37. Kosmider, G.; M. Young; G. Kinney: Studies in Display Legibility: Part VIII. Legibility of Common Five-Letter Words, AD-633-055, the Mitre Corp., May 1966
38. Belmont, P. A.: Font Recognition, AD-660-125, Technical Report No. RADC-TR-67-348, Rome Air Development Center, New York, October 1967
39. Shurtleff, D. and D. Owens: Studies of Display Symbol Legibility: Part VII. Comparison of Displays at 945- and 525-Line Resolutions, AD-633-649, the Mitre Corp., May 1966
40. Kinney, Jo Ann S. and Jane C. Cooper: Report Number 499, Adaption to a Homochromatic Visual World, AD-659-496, Naval Submarine Medical Center, July 1967

REFERENCES (Cont)

41. Mercier, A.; G. Perdriel; TCD. Whiteside: AGARDograph No. 107, Problems of Vision in Low Level Flight, Aerospace Medical Panel of AGARD, 1965
42. Irland, F. H.; W. Kinslow; E. Levin; D. Page: Experimental Study of the Effects of Surround Brightness and Size on Visual Performance, AMRL-TR-67-102, Aerospace Medical Research Laboratories, September 1967
43. Winblade, R. L.: Current Research on Advanced Cockpit Display Systems, Report No. 491, AGARD Flight Mechanics Panel, October 1964
44. Mast, L. T.; L. D. Amdahl; O. T. Gatlo; A. A. B. Pritsker: Growth of Automation in Apollo Prelaunch Checkout: Volume II. Added Roles, RM-4161-NASA, The Rand Corp., California, 1964
45. Gagliardi, U. O.: Man-Computer Relationship in Fault Isolation, 510-TM-9, Dunlap & Associates, Inc., Connecticut, June 1965
46. Pepler, R. D.: Functional Requirements for the Saturn V Display System, Dunlap & Associates, Inc., Connecticut, June 1965
47. Affinito, F. J. and J. G. Wohl: Data Conditioning and Display for Apollo Prelaunch Checkout-Servo Response Display Technique, 675-TM-7, Dunlap & Associates, Inc., Connecticut
48. Grant, G. and J. H. Nichols: Data Conditioning and Display for Apollo Prelaunch Checkout - Signal Flow Display Technique, 675-TM-5, Dunlap & Associates, Inc., Connecticut, August 1966
49. Gaxley, Jr., C.; J. E. Rieber; R. H. Stratton: Pseudo-Color Processing of Electronic Photographs, Rand Corporation, California, April 1967
50. DeArmond, F. B. and A. Ralph Lombardo: Minuteman II Aerospace Ground Equipment - Self-Test Features and Status Display Techniques, North American Aviation, Inc., California
51. Kleiman, E. B.: A Survey of Various Information Display Devices, AD-653-867, Naval Training Device Center, May 1967
52. Weitzman, C.: Current and Future Graphic Displays for Military Systems, Computer Design, February 1973, P. 65
53. Fink, D. G.: Television Engineering, McGraw-Hill Book Co., Inc., New York, 1952
54. Wyszecki and Stiles: Color Science, Wiley, New York, 1967
55. Woodson and Conover: Human Engineering Guide for Equipment Engineers, University of California Press, Berkeley, L. A., 1964

REFERENCES (Cont)

56. VanCott and Kindade: Human Engineering Guide to Equipment Design, U. S. Government Printing Office, Washington, D. C., 1972
57. Billmeyer and Saltzman: Principles of Color Technology, Interscience Publishers, 1966
58. Goodman: A Beam Index Single-Gun Color Cathode Ray Tube with Rear Optical Projection Capability
59. Elson, B. M.: Tricolor Display Panels Developed, Aviation Week & Space Technology, January 17, 1972
60. Mercier and Whiteside: The Effect of Red Versus White Instrument Lighting on the Dark Adaption Index, Flying Research Committee, May 1966
61. Goodman: An Automatic Test System Based Upon Pattern Recognition Displays
62. What's New in Small Displays, IEEE Spectrum 1972
63. Barnett and Heumann: Seeing Red, Yellow, and Green in Semiconductor Alphanumeric Display, Electronics, May 11, 1970
64. Toward Large Color Displays: Eliminating Film from the Picture, Electronics, July 25, 1966
65. CORAD (Color Radar), Proceedings of the IEEE, July 1967
66. Passavant, F. C.: Multicolor Cathode Ray Tube Displays, Computer Design, January 1970
67. Bryden, J. E.: Design Considerations for Computer Driven CRT Displays, Computer Design, March 1969
68. Smith, S. L.: Color Coding and Visual Separability in Information Displays, Journal of Applied Psychology, 1963, Vol. 47, No. 6, 358-364
69. Smith, S. L. and Thomas, D. W.: Color Versus Shape Coding in Information Displays, Journal of Applied Psychology, June 1964, Vol. 48, No. 3
70. Le Grand, Yves: Light, Colour and Vision, Chapman & Hill Ltd., London, England, 1968
71. IES Lighting Handbook, Illuminating Engineering Society, 1962